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CONSUMPTIVE USE OF WATER

By Harry F. Blaney, M. ASCE

IRRIGATION DIVISION

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AMERICAN SOCIETY OF CIVIL ENGINEERS
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PAPERS

CONSUMPTIVE USE OF WATER

BY HARRY F. BLANEY,[1] M. ASCE

SYNOPSIS

Consumptive use (or evapo-transpiration) includes loss of water by evaporation of moisture from the surface of the soil and loss from interception by vegetative cover and plant transpiration. This paper discusses the subject of consumptive use with special reference to definitions, methods, and results of research. The procedure for determining consumptive use of water in valley areas from climatology, irrigation, and other data is outlined. The results of experimental measurements of evapo-transpiration by agricultural crops and natural vegetation are presented briefly. The paper provides the practicing engineer the information required to estimate consumptive use in water utilization investigations.

INTRODUCTION

Knowledge concerning the various phases of the hydrologic cycle is incomplete. Consumptive use of water (or evapo-transpiration) is one of the important elements in this cycle of water movement from the time water falls on the land as rain or snow until it reaches the ocean. The subject of consumptive use includes evaporation of moisture from land and transpiration by vegetation and is increasingly significant, particularly in the irrigated areas of the western part of the United States. It involves problems of water supply both surface and underground, as well as those of the management of, and general economics of, irrigation and multiple-purpose projects. Data on the use of water are essential in planning federal, state, and private irrigation projects. The consumptive-use requirement for water has become an important factor in the arbitration of controversies regarding major stream systems, such as the Rio Grande and the Colorado River, in which the welfare

NOTE.—Written comments are invited for publication; the last discussion should be submitted by April 1, 1952.

[1] Senior Irrigation Engr., Div. of Irrigation and Water Conservation, Soil Conservation Service, Research, U. S. Dept. of Agriculture, Los Angeles, Calif.

of the people of valleys, cities, states, and even nations is involved.[2,3] Before the available water resources and an equitable division of the use of the waters of a drainage basin in arid and semiarid regions can be satisfactorily ascertained, careful consideration must be given to the consumptive-use requirements for water in various subbasins.[3,4]

In water-supply and irrigation investigations, engineers are called upon to make, within a limited time, estimates of probable past, present, and future evaporation and evapo-transpiration losses from areas in river valleys. Sometimes few long-period hydrologic records, except climatological data, are available.[3] The results of research on evapo-transpiration provide the practicing engineer with the basic data and methods required to estimate consumptive use in utilization of water investigations.[4] A progressive improvement of methods and rapid increase in available literature on the subject sometimes make it difficult and tedious for the engineer who does not specialize in this field to evaluate the data properly and select the methods best suited for solving his particular problem.

Definitions and Some Interpretations

Definition of Consumptive Use.—In some instances there has been confusion as to the meaning of terms employed in reports on the use of water. Such terms as consumptive use, evapo-transpiration, transpiration, total evaporation, stream-flow depletion, water requirements, irrigation requirements, and duty of water have been interchanged. In this paper the terms "consumptive use" and "evapo-transpiration" are considered synonymous. They may be defined as:

> "The sum of the volumes of water used by the vegetative growth of a given area in transpiration and building of plant tissue and that evaporated from adjacent soil, snow, or intercepted precipitation on the area in any specified time, divided by the given area. If the unit of time is small, the consumptive use is expressed in acre-inches per acre or depth in inches, whereas, if the unit of time is large, such as a crop-growing season or a 12-month period, the consumptive use is expressed as acre-feet per acre or depth in feet or inches."

This definition has been found satisfactory for use in many reports since 1935.[2,3,4] In 1939 it was adopted with minor changes by the Committee on Irrigation of the American Society of Agricultural Engineers and is now in general use by engineers.

Other Interpretations.—Although evaporation and transpiration have been studied for more than 200 years, the term consumptive use probably was not applied to water consumption prior to 1900. Many of the writings concerning the consumptive use of water are in the form of unpublished engineering reports. The term consumptive use, as originally applied to irrigation, was defined

[2] "Water Utilization, Upper Rio Grande Basin," by Harry F. Blaney, Paul A. Ewing, O. W. Israelsen, Carl Rohwer, and F. C. Scobey, National Resources Committee, Washington, D. C., February, 1938, Part III.

[3] "Consumptive Use of Water in the Irrigated Areas of Upper Colorado River Basin," by Harry F. Blaney and Wayne D. Criddle, Div. of Irrigation and Water Conservation, Soil Conservation Service, U. S. Dept. of Agriculture, Logan, Utah, April, 1949.

[4] "Consumptive Water Use and Requirements: Report of the Participating Agencies, Pecos River," by Harry F. Blaney, Paul A. Ewing, Karl V. Morin, and Wayne D. Criddle, Joint Investigation of the National Resources Planning Board, Washington, D. C., June, 1942.

as a seasonal loss of water in acre-feet per acre irrigated. Among the first published writings dealing directly with the consumptive use, a report of an ASCE committee in 1930 is noteworthy.[5] The committee proposed certain definitions for consumptive use of water in a basic sense, and also for the farm, the project, and the valley. It also reviewed previous estimates of consumptive use for large river systems and made reference to 24 articles, published and unpublished, dealing with net water requirements and consumptive use. One of the definitions suggested by this committee follows:

> "Consumptive Use in a Basic Sense: The consumptive use, 'U', is here defined as the quantity of water, in acre-feet per cropped acre per year, absorbed by a crop and transpired or used directly in the building of plant tissue, together with that evaporated from the crop-producing land."

In a report[6] in 1930 on rainfall penetration and consumptive use of water, consumptive use was defined as "the sum of water used by the vegetative growth of a given area in transpiration or building of plant tissue and that evaporated from the area."

In 1934, the Committee on Absorption and Transpiration, Hydrology Section, American Geophysical Union, proposed the following definition[7]:

> "Consumptive Use: The quantity of water per annum used by either cropped or natural vegetation in transpiration or in the building of plant-tissue, together with water evaporated from the adjacent soil, snow, or from intercepted precipitation. It is sometimes termed 'evapo-transpiration'."

In 1935 the ASCE Special Committee of the Board of Direction, on Irrigation Hydraulics, adopted the following definitions[8]:

"Consumptive Use: The quantity of water transpired and evaporated from a cropped area."

"Evapo-transpiration: Combined loss of water from soils by evaporation and plant transpiration."

In some reports, the term "total evaporation" is applied to the combined evaporation and transpiration loss in drainage basins.[9]

The handbook[10] of the ASCE Committee on Hydrology of the Hydraulics Division of the American Society of Civil Engineers, published in 1949, states:

> "* * * the terms 'evapo-transpiration' and 'consumptive use' have received general acceptance, these terms denote the quantity of water

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[5] "Consumptive Use of Water in Irrigation," Progress Report of the Duty of Water Committee of the Irrigation Division, *Transactions*, ASCE, Vol. 94, 1930, p. 1349.

[6] "Rainfall Penetration and Consumptive Use of Water In Santa Ana River Valley and Coastal Plain," by Harry F. Blaney, Colin A. Taylor, and Arthur A. Young, *Bulletin No. 33*, Div. of Water Resources, California State Dept. of Public Works, Pomona, Calif., 1930.

[7] "Transactions of the American Geophysical Union," National Research Council of the National Academy of Sciences, Washington, D. C., June, 1934, Part II.

[8] "Letter Symbols and Glossary for Hydraulics," by the Special Committee for Irrigation Hydraulics, ASCE, *Bulletin No. 11*, 1935.

[9] "Hydrology," *Physics of the Earth Series*, Vol. IX, ed. by O. E. Meinzer, McGraw-Hill Book Co., Inc., New York, N. Y., 1942, p. 314.

[10] "Evaporation and Transpiration," in Hydrology Handbook, *Manuals of Engineering Practice—No. 28*, Hydrology Committee of Hydraulics Division, ASCE, 1949, Chapter 4.

transpired by plants during their growth or retained in the plant tissue, plus the moisture evaporated from the surface of the soil and the vegetation, expressed in feet or inches depth of water lost or used in a specified time."

The definitions of other terms which are sometimes confused with consumptive use are as follows:

1. Duty of water: The quantity of irrigation water applied to a given area for the purpose of maturing its crop;
2. Irrigation requirement: The quantity of water, exclusive of precipitation, that is required for crop production. It includes surface evaporation and other economically unavoidable wastes;
3. Stream-flow depletion: The amount of water that flows into a valley, or onto a particular land area, minus the amount that flows out of the valley or off from the particular land area[2];
4. Transpiration: The quantity of water absorbed by the crop and transpired and used directly in the building of plant tissue, in a specified time. It does not include soil evaporation;
5. Water requirement: The quantity of water, regardless of its source, required by a crop in a given period of time, for its normal growth under field conditions. It includes surface evaporation and other economically unavoidable wastes.

Research Studies

Factors Affecting Consumptive Use.—Many factors operate singly or in combination to influence the amount of water consumed by plants. The effects of these factors are not necessarily constant but may fluctuate from year to year as well as from place to place. Some involve the human factor, but others are related to natural influences and the environment.

The rate of evapo-transpiration depends on climate, soil-moisture supply, vegetative cover, soils, and land management. The factors included in climate that particularly affect consumptive use are precipitation, temperature, humidity, wind movement, and length of growing season. The quantity of water transpired by plants depends upon the amount of water at their disposal, as well as on temperature and dryness of the air, wind movement, the intensity of sunlight, the stage of the development of the plant, the amount of its foliage, and the nature of its leaf.

The effect of sunshine and heat in stimulating transpiration was studied as early as 1691, according to a review of the literature by Cleveland Abbe.[11] Measurements of transpiration of various kinds of plants by L. J. Briggs and H. L. Shantz indicate a close correlation between transpiration and evaporation from free water surfaces, air temperature, solar radiation, and wet-bulb depression readings.[12] Scientists have made many other studies of the effects of temperature moisture and light on plant growth.[13]

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[11] "A First Report of the Relations Between Climates and Crops," by Cleveland Abbe, *Bulletin No. 36*, Weather Bureau, U. S. Dept. of Agriculture, Washington, D. C., 1905.

[12] "Daily Transpiration During the Normal Growth Period and its Correlation with the Weather," by L. J. Briggs and H. L. Shantz, *Journal of Agricultural Research*, Vol. 7, 1916.

[13] "The Water Requirements of Plants," by Lyman J. Briggs and H. L. Shantz, *Bulletin No. 284*, Bureau of Plant Industry, U. S. Dept. of Agriculture, Washington, D. C., 1913.

Studies and Results.—Research studies by federal, state, and other type agencies have been made on evaporation from soil and evapo-transpiration at various times during the past fifty years in the United States.

One of the first studies[14] of evapo-transpiration losses of irrigated crops in California was made in 1903 by Irrigation Investigations, Office of Experiment Stations, United States Department of Agriculture (USDA). At various times since that date this agency, now known as the Division of Irrigation and Water Conservation of the Soil Conservation Service, has studied and measured consumptive use of water by different agricultural crops and natural vegetation in many sections of the West, in cooperation with state engineers as well as state agricultural experiment stations, and other agencies. Usually evaporation, temperature, humidity, precipitation, and wind movement were recorded at the same time. Thus, data are available in many areas for correlating consumptive use measurements with temperature and other climatological observations.

Extensive studies in the correlation of evaporation, temperature, humidity, wind movement, and evapo-transpiration were conducted by the author in 1919, at the Irrigation Field Laboratory of the USDA, located at Denver, Colo. These studies included meteorological observations as well as measurements of evaporation from various sized pans, evaporation from soil tanks, and consumptive use of water by irrigated crops grown in tanks.[15]

The results of these studies and other investigations in California, New Mexico, and other areas indicate the observed evaporation data may be used as a means of estimating evapo-transpiration by phreatophytes (water-loving vegetation) having access to an ample water supply when the relation of the two is known for a particular area.[2,4] As an example, for two locations in California, for tules growing in large tanks within the confines of a swamp area, the consumptive use, with reference to evaporation from a near-by exposed Weather Bureau pan, was 95%. The percentage varied from month to month, increasing during the summer and becoming smaller in the cooler months, but 95% was the average obtained from a two-year record.

TABLE 1.—COEFFICIENTS FOR CONSUMPTIVE USE OF WATER, CARLSBAD, NEW MEXICO—1940

Type of vegetation	Depth of water table (feet)	Empirical Coefficients	
		k_w	k_s
Sacaton	4	0.0044	0.0139
Sacaton	2	0.0063	0.0154
Salt cedar (tamarisk)	2	0.0075	0.0216

From long-period records of evaporation, temperature, and humidity in New Mexico and Texas, together with consumptive-use measurements at Carlsbad, N. Mex., empirical formulas were developed for computing evaporation and consumptive use when temperature and humidity data are available.[4] Consideration of these results and the factors involved is shown in the ex-

[14] "Evaporation Losses in Irrigation and Water Requirements of Crops," by Samuel Fortier, *Bulletin No. 177*, Office of Experiment Stations, U. S. Dept. of Agriculture, Washington, D. C., 1907.

[15] "Progress Report on Evaporation and Use of Water Studies at Denver Irrigation Field Laboratory, Colorado," by Harry F. Blaney, Div. of Irrigation, U. S. Dept. of Agriculture, Los Angeles, Calif., 1920 (unpublished).

pression:

$$u = k\,t\,p\,(114 - h) = k\,c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which u is the monthly consumptive use (or evaporation) in inches; k is the monthly empirical coefficients; t is the mean monthly temperature, °F; p is the monthly percentage of daytime hours of the year; h is the average monthly

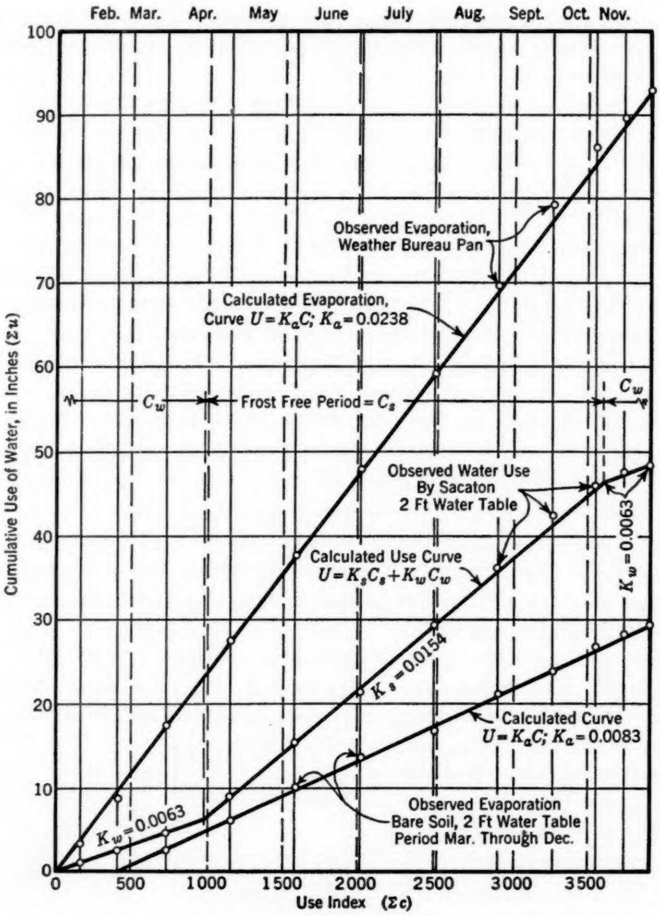

FIG. 1.—OBSERVED AND CALCULATED CURVES FOR USE OF WATER, CARLSBAD, NEW MEXICO, 1940

humidity; and $c = t\,p\,(114 - h)$ is the monthly use index (climatic factor). The formula for annual consumptive use (or evaporation) in inches is

$$U = K_a\,C = K_w\,c_w + k_s\,c_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

in which K_a is the empirical coefficient for the entire year; C is the use index for entire year; k_w is the empirical coefficient for winter period; k_s is the empir-

ical coefficient for growing season or frost-free period; c_w is the use index for winter season; and c_s is the use index for growing season or frost-free period.

The values of k_w and k_s may be computed from observed values of consumptive use, temperature, and humidity by the relation $k = u/c$.

Computed coefficients for winter and summer consumptive use of water for natural vegetation (phreatophtes) growing along the Pecos River, based on evapo-transpiration, temperature, and humidity measurements at Carlsbad for the year 1940, are shown in Table 1. The computed annual coefficient K for lake-surface evaporation is 0.0164. The summer coefficient for alfalfa, growing in an area of high water table at Albuquerque, N. Mex., in 1936, is computed to be $k_s = 0.0170$.

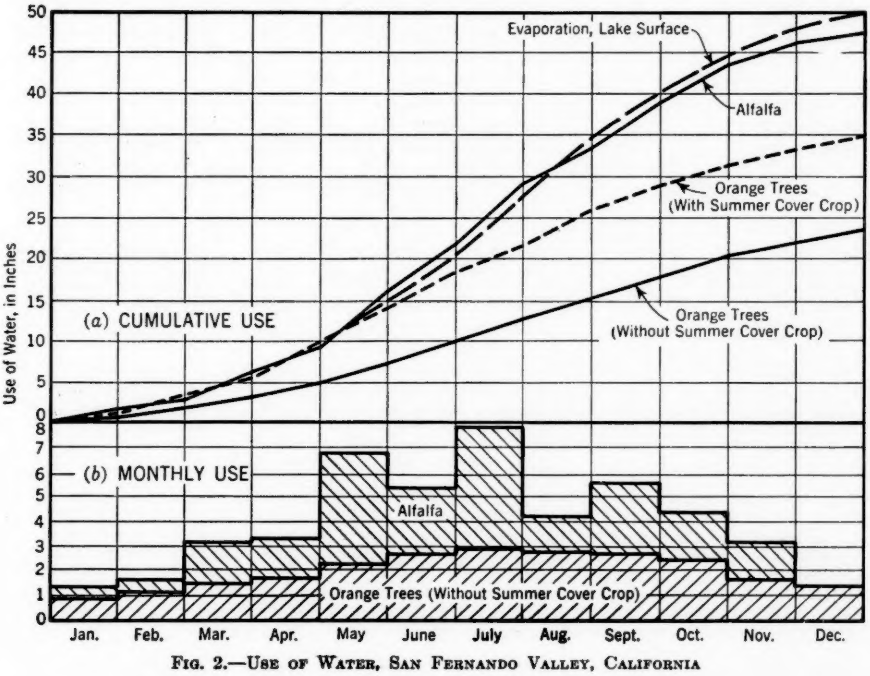

FIG. 2.—USE OF WATER, SAN FERNANDO VALLEY, CALIFORNIA

Fig. 1 shows the observed and calculated curves for use of water for evaporation from a Weather Bureau pan, a tank of sacaton growth, and bare soil tank at Carlsbad in 1940. An example of the results of research studies of the transpiration use of water is shown in Fig. 2 which illustrates the difference between evaporation from a lake surface and the use of water by alfalfa and citrus trees in the San Fernando Valley, Calif.[16]

The results of some measurements by various investigators of consumptive use by agricultural crops and natural vegetation are shown in Tables 2 and 3, respectively.

[16] "Progress Report on Cooperative Research Studies on Water Utilization, San Fernando Valley, California, Irrigation Season of 1950," by Harry F. Blaney and Homer J. Stockwell, Jr., Div. of Irrigation, Soil Conservation Service, U. S. Dept. of Agriculture, June, 1941 (unpublished).

TABLE 2.—SEASONAL CONSUMPTIVE USE OF WATER BY VARIOUS IRRIGATED CROPS AS DETERMINED BY FIELD EXPERIMENTS

Location	Growing Season or Period		Year	Consumptive use of water (inches)	Authority
	From	To			
(1)	(2)	(3)	(4)	(5)	(6)
			(a) ALFALFA		
Bonners Ferry, Idaho	May 5	September 25	1940–1947	24.0	Marr and Criddle[a]
Carlsbad, N. Mex.	April 18	November 10	1940	38.6	Blaney[b]
Davis, Calif.	April 1	September 30	1939	30.4	Veihmeyer[c]
Fort Stockton, Tex.	April 13	November 11	1940	40.5	Blaney and Bloodgood[b]
Logan, Utah	May 7	October 11	1902–1929	25.0	Pittman and Stewart[d]
San Fernando, Calif.	April 1	October 31	1940	37.4	Blaney and Stockwell[e]
			(b) CORN		
Davis, Calif.	June 1	September 30	...	12.0	Veihmeyer[c]
Logan, Utah	June 1	September 30	1902–1929	25.0	Pittman and Stewart[d]
Vernal, Utah	June 10	September 20	1948	19.4	Criddle and Peterson[f]
			(c) COTTON		
Bakersfield, Calif.	April 1	October 31	1927–1930	29.2	Beckett and Dunshee[g]
Fort Stockton, Tex.	April 13	November 11	1940	28.9	Blaney and Bloodgood[b]
Los Banos, Calif.	May 1	November 30	1932	25.5	Adams and Veihmeyer[h]
Mesa, Ariz.	April 1	October 31	1935	30.9	Harris and Hawkins[i]
			(d) SMALL GRAINS		
Bonners Ferry, Idaho	May 5	August 5	1930–1947	17.5	Marr and Criddle[a]
Logan, Utah	May 10	August 10	1902–1929	17.5	Pittman and Stewart[d]
San Luis Valley, Colo.	June 1	August 31	1936	14.05	Blaney[b]
Scottsbluff, Nebr.	April 20	July 25	1932–1933	14.72	Bowen[j]
			(e) ORCHARD CROPS—ORANGES		
Azusa, Calif.	April 1	October 31	1929	21.8	Blaney and Taylor[k]
Mesa, Ariz.	March 1	October 31	1931–1934	32.4	Harris and Kinnison[l]
Tustin, Calif.	April 1	October 31	1929	20.9	Beckett and Pillsbury[m]
			(f) ORCHARD CROPS—WALNUTS		
Tustin, Calif.	April 1	September 30	1928	26.30	Beckett[n]
Tustin, Calif.	April 1	September 30	1929	27.43	Beckett[n]
			(g) ORCHARD CROPS—DECIDUOUS TREES		
Albuquerque, N. Mex.	May 1	September 31	1936	19.5	Blaney[b]
Davis, Calif.	March 1	November 30	...	26.4	Veihmeyer[c]
Wenatchee, Wash.	April 15	October 22	1908	23.0	Fortier[o]
Ontario, Calif.	April 1	September 30	1928	28.4	Blaney and Taylor[k]
			(h) POTATOES		
Bonners Ferry, Idaho	May 8	September 27	1947	22.95	Marr and Criddle[a]
Logan, Utah	May 20	September 15	1902–1929	15.0	Pittman and Stewart[d]
Ontario, Ore.	April 20	August 31	1941–1942	17.9	Sanford and Criddle[p]
San Luis Valley, Colo.	June 1	September 30	1936	19.89	Blaney[b]

TABLE 2.—*Continued*

Location (1)	Growing Season or Period: From (2)	Growing Season or Period: To (3)	Year (4)	Consumptive use of water (inches) (5)	Authority (6)
		(*i*) Sugar Beets			
Davis, Calif.	April 1	September 30	...	25.20	Veihmeyer[c]
Logan, Utah	April 15	October 15	1902–1929	25.0	Pittman and Stewart[d]
Scottsbluff, Nebr.	April 20	October 15	1932–1936	24.0	Bowen[j]
		(*j*) Tomatoes			
Davis, Calif.	June 1	October 31	1933–1935	22.8	Veihmeyer[c]
Mercedes, Tex.	March 25	June 30	1918–1920	17.0	Rockwell[q]
		(*k*) Truck Crops			
Stockton, Calif.	May 1	September 30	1925–1928	21.4	Stout[r]
Stockton, Calif.	April 1	October 31	1925–1928	24.6	Stout[r]

[a] "Consumptive Use of Water Studies in Idaho," by Wayne D. Criddle and James C. Marr, Div. of Irrigation, Soil Conservation Service, U. S. Dept. of Agriculture, Boise, Idaho, 1945.

[b] "Consumptive Water Use and Requirements," by Harry F. Blaney, Karl V. Morin, and Wayne D. Criddle, The Pecos River Joint Investigation Reports of the Participating Agencies, National Resources Planning Board, 1942, pp. 170–230.

[c] "Irrigation Studies," by Frank J. Veihmeyer, Univ. of California, Berkeley, Calif., 1939 (unpublished).

[d] "Twenty-Eight Years of Irrigation Experiments near Logan, Utah," by D. W. Pittman and George Stewart, *Bulletin 219*, Utah Agricultural Experiment Station, 1930, pp. 1–15.

[e] "Progress Reports on Cooperative Research Studies of Water Utilization, San Fernando Valley, Calif.," by Harry F. Blaney and Homer J. Stockwell, 1940–41 (unpublished).

[f] "Consumptive Water Use and Requirements: A Progress Report on Colorado River Area Investigations in Utah," by Wayne D. Criddle and Dean F. Peterson, Jr., Div. of Irrigation and Utah Agricultural Experiment Station, Soil Conservation Service, U. S. Dept. of Agriculture, 1949.

[g] "Water Requirements of Cotton on Sandy Loam Soils in Southern San Joaquin Valley," by S. H. Beckett and Carroll F. Dunshee, *Bulletin 537*, California Agricultural Experiment Station, 1932, pp. 1–48.

[h] "Cotton Irrigation Investigations in San Joaquin Valley, California, 1926–1935," by Frank Adams, F. J. Veihmeyer, and Lloyd N. Brown, *Bulletin 668*, California Agricultural Experiment Station, 1942.

[i] "Irrigation Requirements of Cotton on Clay Loam Soils in the Salt River Valley," by Karl Harris and R. S. Hawkins, *Bulletin 181*, Arizona Agricultural Experiment Station, 1942, pp. 421–459.

[j] "Uses and Efficiencies of Water by Some Farm Crops under Irrigation in Western Nebraska," by Leslie Bowen, Div. of Irrigation, Soil Conservation Service, U. S. Dept. of Agriculture, Scottsbluff, Nebr., 1937.

[k] "Rainfall Penetration and Consumptive Use of Water in Santa Ana River Valley and Coastal Plain," by Harry F. Blaney, C. A. Taylor, and A. A. Young, *Bulletin 33*, Div. of Water Resources, California State Dept. of Public Works, 1930, pp. 1–162.

[l] "Use of Water by Washington Navel Oranges and Marsh Grapefruit Trees in Salt River Valley, Arizona," by Karl Harris, A. F. Kinnison, and O. W. Albertt, *Bulletin 153*, Arizona Agricultural Experiment Station, 1936, pp. 441–496.

[m] "Irrigation Requirements of California Crops," by Arthur A. Young, *Bulletin 51*, Div. of Water Resources, California State Dept. of Public Works, 1945, pp. 1–132.

[n] "Irrigation Requirements in Southern California," by S. H. Beckett, *Bulletin 32*, Div. of Water Resources, California State Dept. of Public Works, 1930, Chapter IX, pp. 57–60.

[o] "Orchard Irrigation," by Samuel Fortier, *Farmers' Bulletin 1518*, U. S. Dept. of Agriculture, 1927, pp. 1–27.

[p] Studies (unpublished) of Hollis Sanford, and Wayne D. Criddle, 1941–1943.

[q] "Duty of Water in Irrigation," by William L. Rockwell, Div. of Irrigation and Texas Board of Water Engineers, Bureau of Public Roads, U. S. Dept. of Agriculture, 1914–1920.

[r] "Consumptive Use of Water in the Delta of Sacramento and San Joaquin Rivers," by O. V. P. Stout, *Bulletin 27*, Div. of Water Resources, Calif. State Dept. of Public Works, 1931, pp. 68–75.

Methods of Determining Water Use

Scientists have tried various means to determine the amount of water transpired by plants.[9] One of the earliest methods consisted of weighing freshly cut leaves, twigs, or stalks of growing plants immediately after cutting and at short intervals thereafter, during a period of hours or days, or until wilting commenced. Experimenters have also grown thousands of individual plants in small pots, weighing them periodically to determine the transpiration

TABLE 3.—Annual or Seasonal Consumptive Use of Water by Native Vegetation as Determined by Tanks and Soil Moisture Studies in Valley Areas

Location	Vegetation	Depth to water table (inches)	Period			Consumptive use (inches)	Authority
			From	To	Months		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			(a) Native Grass				
San Bernardino, Calif.	....	....[a]	Oct. 1928	Sept. 1929	12	10.0	Blaney and Taylor[b]
Ontario, Calif.	....	....[a]	Oct. 1927	Sept. 1928	12	13.4	Blaney and Taylor[b]
Anaheim, Calif.	....	....[a]	Oct. 1927	Sept. 1928	12	12.6	Blaney and Taylor[b]
Cucamonga, Calif.	....	....[a]	Oct. 1929	Sept. 1930	12	15.0	Blaney and Taylor[b]
			(b) Native Brush				
San Bernardino, Calif.	....	....[a]	Oct. 1927	Sept. 1930	12	21.6	Blaney and Taylor[b]
Muscoy, Calif.	....	....[a]	Oct. 1927	Sept. 1928	12	17.7	Blaney and Taylor[b]
Palmer Canyon, Calif.	....	....[a]	Oct. 1929	Sept. 1930	12	19.6	Blaney and Taylor[b]
			(c) Salt Grass				
Owens Valley, Calif.	....	18	Jan. 1911	Dec. 1911	12	48.8	Lee[c]
Owens Valley, Calif.	....	35	Jan. 1911	Dec. 1911	12	40.2	Lee[c]
Owens Valley, Calif.	....	59	Jan. 1911	Dec. 1911	12	13.4	Lee[c]
Santa Ana, Calif.	....	12	May 1931	Apr. 1932	12	42.8	Blaney and Taylor[d]
Santa Ana, Calif.	....	24	May 1931	Apr. 1932	12	35.3	Blaney and Taylor[d]
Santa Ana, Calif.	....	36	June 1931	Apr. 1932	11	23.8	Blaney and Taylor[d]
Santa Ana, Calif.	....	48	May 1931	Apr. 1932	12	13.4	Blaney and Taylor[d]
San Luis Valley, Colo.	....	14	Apr. 1928	Oct. 1928	7	17.8	Tipton and Hart[e]
San Luis Valley, Colo.	....	24	Apr. 1928	Oct. 1928	7	15.6	Tipton and Hart[e]
Los Griegos, N. Mex.	....	14	Oct. 1926	Sept. 1927	12	33.2	Elder[e]
Los Griegos, N. Mex.	....	26	Oct. 1927	Sept. 1928	12	22.7	Elder[e]
Isleta, N. Mex.	....	8	June 1936	May 1937	12	31.5	Blaney and Morin[e]
Mesilla Valley, N. Mex.	....	14	July 1936	June 1937	12	39.8	Blaney[e]
Escalante Valley, Utah	....	23	May 1927	Oct. 1927	6	22.6	White[f]
Escalante Valley, Utah	....	26	May 1927	Oct. 1927	6	17.9	White[f]
			(d) Trees				
San Luis Rey, Calif.	Cottonwood, willows, grass	48	Apr. 1941	Mar. 1943	12	62.5	Muckel and Blaney[g]
Safford Valley, Ariz.	Cottonwood, willows, grass	84	Oct. 1943	Sept. 1944	12	91.7	Gatewood and Robinson[h]
Safford Valley, Ariz.	Tamarisk	83.6	Oct. 1943	Sept. 1944	12	87.8	Gatewood and Robinson[h]
Safford Valley, Ariz.	Tamarisk	24	May 1940	Dec. 1940	8	61.1	Turner and Halpenny[i]
Safford Valley, Ariz.	Tamarisk	48	May 1940	Dec. 1940	8	47.9	Turner and Halpenny[i]
Carlsbad, N. Mex.	Tamarisk	36	Jan. 1940	Dec. 1940	12	57.3	Blaney and Morin[j]
Safford Valley, Ariz.	Mesquite	120	Oct. 1943	Sept. 1944	12	32.5	Gatewood and Robinson[h]

TABLE 3.—*Continued*

Location	Vegetation	Depth to water table (inches)	Period			Consumptive use (inches)	Authority
			From	To	Months		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			(e) Miscellaneous Vegetation				
Safford Valley, Ariz.....	Baccharis	24	May 1940	Dec. 1940	8	52.0	Turner and Halpenny[i]
Safford Valley, Ariz.....	Baccharis	48	May 1940	Dec. 1940	8	39.7	Turner and Halpenny[i]
Safford Valley, Ariz.....	Baccharis	72	Oct. 1943	Sept. 1944	12	54.2	Gatewood and Robinson[h]
Escalante Valley, Utah.	Grease wood	26	May 1927	Oct. 1927	6	25.2	White[f]
San Luis Valley, Colo...	Meadow grass	0	June 1936	Nov. 1936	6	36.3	Blaney and Morin[j]
Carlsbad, N. Mex.......	Sacaton	36	Jan. 1940	Dec. 1940	12	44.8	Blaney and Morin[j]
San Bernardino, Calif...	Bermuda grass	24	May 1929	Apr. 1931	12	34.4	Blaney and Young[d]
Fort Collins, Colo......	Sedge grass	6	May 1930	Oct. 1930	6	60.2	Parshall[k]
Fort Collins, Colo......	Sedge grass	18	May 1930	Oct. 1930	6	53.6	Parshall[k]
Isleta, N. Mex.........	Sedge grass	3	June 1936	May 1937	12	76.9	Blaney and Morin[l]
Santa Ana, Calif........	Wire rush	24	Aug. 1930	July 1931	12	78.9	Blaney and Young[d]
Fort Collins, Colo......	Rushes	....	July 1931	Oct. 1931	4	52.6	Parshall[k]
Victorville, Calif........	Tules	0	Jan. 1931	Dec. 1932	12	78.4	Blaney and Taylor[d]
San Luis Valley, Colo...	Tules	0	June 1936	Nov. 1936	6	38.8	Blaney[e]

[a]Determined by Soil Sampling. No high water table. [b] "Rainfall Penetration and Consumptive Use of Water in Santa Ana River Valley and Coastal Plain," by H. F. Blaney, Colin A. Taylor, and Arthur A. Young, *Bulletin No. 33*, Div. of Water Resources, California State Dept. of Public Works, Pomona, Calif., 1930. [c] "Hydrology," *Physics of the Earth Series*, ed. by O. E. Meinzer, McGraw-Hill Book Co., Inc., New York, N. Y., 1942, p. 295. [d] "Water Losses Under Natural Conditions from Wet Areas in Southern California," by Harry F. Blaney, C. A. Taylor, M. G. Nickle, and A. A. Young, *Bulletin No. 44*, Div. of Water Resources, California State Dept. of Public Works, Pomona, Calif., 1933. [e] "Water Utilization, Upper Rio Grande Basin," by Harry F. Blaney, Paul A. Ewing, O. W. Israelsen, Carl Rohrer, and F. C. Scobey, National Resources Committee, Washington, D. C., February, 1938, Part III. [f] "A Method of Estimating Ground-Water Supplies Based on Discharge by Plants and Evaporation from Soil," Results of Investigations in Escalante Valley, Utah, by W. N. White, *Water-Supply Paper 659-A*, Geological Survey, U. S Dept. of the Interior, Washington, D. C., 1932. [g] "Utilization of the Waters of Lower San Luis Rey Valley, San Diego County, California," by Dean C. Muckel and Harry F. Blaney, Div. of Irrigation and Water Conservation, Soil Conservation Service, U. S. Dept. of Agriculture, Los Angeles, Calif., April, 1945. [h] "Use of Water by Bottom-Land Vegetation in Lower Safford Valley, Arizona," by J. S. Gatewood, T. W. Robinson, B. R. Colby, J. D. Hem, and L. C. Halpenny, *Water-Supply Paper No. 1103*, Geological Survey, U. S. Dept. of the Interior, Washington, D. C., 1950. [i] "Ground-Water Inventory in the Upper Gila River Valley, New Mexico and Arizona: Scope of Investigations and Methods Used," by S. F. Turner and L. C. Halpenny, *Transactions*, Am. Geophysical Union, 1941, Part III, Washington, D. C., August, 1941, p. 738. [j] "Consumptive Water Use and Requirements: Report of the Participating Agencies, Pecos River," by Harry F. Blaney, Paul A. Ewing, Karl V. Morin, and Wayne D. Criddle, Joint Investigation of the National Resources Planning Board, Washington, D. C., June, 1942. [k] "Use of Water by Native Vegetation," by Arthur A. Young and Harry F. Blaney, *Bulletin No. 50*, California State Div. of Water Resources, Sacramento, Calif., 1942.

or evapo-transpiration losses. Most of the methods of this type are artificial, and it is questionable whether the results can be extended to field conditions.

Various methods have been used by engineers to determine consumptive use of water by agricultural crops and natural vegetation under field conditions.[17] Regardless of the method, the problems encountered are numerous. The source of water used by plant life, whether from precipitation alone or irrigation or ground water plus precipitation, is a factor in selecting a method. The methods most widely used in engineering investigations are:

(*a*) soil-moisture studies on plots;
(*b*) tank or lysimeter experiments;
(*c*) ground-water fluctuations;
(*d*) inflow-outflow measurements;
(*e*) integration;

[17] "Field Methods of Determining Consumptive Use of Water," by Harry F. Blaney, Div. of Irrigation, U. S. Dept. of Agriculture, Los Angeles, Calif., 1938.

(*f*) effective heat;
(*g*) correlation of water use, climatological data, and other data; and
(*h*) analysis of irrigation and precipitation records.

Soil-Moisture Studies on Plots.—This method is usually employed to determine the consumptive use of irrigated field plots in which the soil is fairly uniform and the depth to ground water is such that it will not influence the soil-moisture fluctuations within the root zone. Soil samples are taken by means of a standard soil tube before and after each irrigation, with some samples between irrigations. The samples are in 6-in. sections for the first foot and thereafter in 1-ft sections in the major root zone. Usually a great number of soil samples must be taken.[6,18]

Standard laboratory practices are used in determining the moisture content of the soil samples. The samples are weighed and dried in an electric oven at 110° C and the dry weights determined. The water content of a sample is expressed as a percentage of the oven-dry weight of the soil. From the moisture percentage thus obtained, the quantity of water in acre-inches per acre (inches) removed by evaporation and transpiration from each foot of soil is computed by using the formula

$$D = \frac{P\ V\ d}{100} \qquad (3)$$

in which P represents the moisture percentage by weight; V, the apparent specific gravity (or volume weight) of the soil; d, the depth of soil in inches; and D, the equivalent depth of water in inches lost by the soil (acre-inches per acre).

The total number of acre-inches of water extracted from the soil by evapotranspiration is computed for each period and later reduced to equivalent losses in acre-inches or inches for a thirty-day period. The thirty-day period losses may be plotted and a use-of-water curve for the season obtained. The average use of water for each month is taken directly from the curve (see Fig. 1). Examples of monthly consumptive-use-of-water determination made by this method are shown in Table 4 for several crops.

Tank and Lysimeter Experiments.—One of the more common methods of determining use of water by individual agricultural crops and natural vegetation is to grow the plants in tanks or lysimeters and measure the quantity of water necessary to maintain the growth satisfactorily. Tanks as large as 10 ft in diameter and 10 ft deep have been used. However, in most consumptive-use studies, the tanks are about 2 to 3 ft in diameter and 6 ft deep.[6,19]

The practicability of determining consumptive use by means of tanks or lysimeters is dependent on the accuracy of reproduction of natural conditions. In addition to environment, artificial conditions are the result of the limitations of soil, size of tank, or regulation of water supply. Weighing is the precise means of determining the consumptive use from tanks and this method was

[18] "Irrigation Water Requirement Studies of Citrus and Avocado Trees in San Diego County, California, 1926 and 1927," by S. H. Beckett, Harry F. Blaney, and C. A. Taylor, *Bulletin No. 489*, College of Agriculture, Agricultural Experiment Station, Univ. of California, Berkeley, Calif., 1930.

[19] "Use of Water by Native Vegetation," by Arthur A. Young and Harry F. Blaney, *Bulletin No. 50*, California State Div. of Water Resources, Sacramento, Calif., 1942.

used as early as 1907. However, conditions and facilities will not always permit the weighing of tanks. It has been found that all tank vegetation must be protected from the elements by a surrounding growth of the same species. Soil tanks equipped with suitable supply tanks have been used successfully in evapo-transpiration measurements from water tables at various depths. This equipment was recommended by the National Resources Committee. The tanks best adapted for this use are the double-type tank with an annular space between the inner and outer shells.[6,19]

Charles Hamilton Lee, M. ASCE, in tests conducted in Owens Valley, Calif., 1911, employed tanks to measure the use of water by natural vegetation.[9] Since 1919 this method has been employed in California, Colorado, and New Mexico.[2,4,6]

TABLE 4.—Monthly Consumptive Use of Water as Determined by Soil Moisture Studies

Month	Consumptive Use of Water (Inches)							
	Oranges[a]	Peaches[b]	Alfalfa	Alfalfa	Cotton	Cotton	Beets	Potatoes
	(Los Angeles, Calif.)	(Ontario, Calif.)	(Los Angeles, Calif.)[a]	(Scottsbluff, Nebr.)	(Bakersfield, Calif.)	(Mesa, Ariz.)[c]	(Scottsbluff, Nebr.)	(Scottsblufl, Nebr.)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
April	2.2	1.0	3.3	....	0.8	1.1	....	....
May	2.2	3.5	6.7	4.0	1.1	2.2	1.9	....
June	3.1	6.7	5.4	7.0	3.3	3.6	3.3	....
July	3.4	8.0	7.8	7.1	5.6	6.0	5.2	3.4
August	3.7	6.5	4.2	6.4	7.7	8.8	6.9	5.8
September	3.1	2.7	5.6	....	6.4	7.2	5.8	4.4
October	2.9	1.4	4.4	....	3.6	2.9	1.1	....
Total	20.6	29.8	37.4	....	28.5	31.8	24.2	....

[a] "Progress Report on Cooperative Research Studies on Water Utilization, San Fernando Valley, California, Irrigation Season of 1940," by Harry F. Blaney and Homer J. Stockwell, Jr., Div. of Irrigation, Soil Conservation Service, U. S. Dept. of Agriculture, June, 1941 (unpublished). [b] "Rainfall Penetration and Consumptive Use of Water in Santa Ana River Valley and Coastal Plain," by Harry F. Blaney, Colin A. Taylor, and Arthur A. Young, *Bulletin No. 33*, Div. of Water Resources, California State Dept. of Public Works, Pomona, Calif., 1930. [c] "Irrigation Studies in Arizona," by Karl Harris, Div. of Irrigation and Water Conservation, Soil Conservation Service, U. S. Dept. of Agriculture (unpublished).

Ground-Water Fluctuations.—Evapo-transpiration losses are indicated by the daily rise and fall of the water table. Diurnal measurements of the ground-water table fluctuations provide a basis for computing consumptive use of water by overlying vegetation. This method has been used successfully by the Geological Survey (USGS), U. S. Dept. of the Interior, in Escalante Valley, Utah; Santa Ana Valley, Calif.; Gila Valley, Ariz.; and other areas.[20,21,22] The procedure used is to install observation wells, equipped with water-stage

[20] "A Method of Estimating Ground-Water Supplies Based on Discharge by Plants and Evaporation from Soil," Results of Investigations in Escalante Valley, Utah, by W. N. White, *Water-Supply Paper 659-A*, Geological Survey, U. S. Dept. of Interior, Washington, D. C., 1932.

[21] "Water Losses under Natural Conditions from Wet Areas in Southern California," Part I, by Harry F. Blaney, C. A. Taylor, M. G. Nickle, and A. A. Young; Part II, by Harold Troxell, *Bulletin No. 44*, Div. of Water Resources, California State Dept. of Public Works, Pomona, Calif., 1933.

[22] "Use of Water by Bottom-Land Vegetation in Lower Safford Valley, Arizona," by J. S. Gatewood, T. W. Robinson, B. R. Colby, J. D. Hem, and L. C. Halpenny, *Water-Supply Paper 1103*, Geological Survey, U. S. Dept. of Interior, Washington, D. C., 1950.

registers, at representative locations in the area under consideration and to obtain graphic records of the ground-water fluctuations. The specific yield of the soil is determined by standard methods. The diurnal cycle, as indicated by the ground-water table, represents a curve showing the relation of consumptive use to ground-water discharge or recharge.

Inflow-Outflow Measurements.—Consumptive use of water by cottonwoods, willows, tules, and other riparian vegetation common to small streams may be determined by measuring the inflow to and the outflow from a selected area by means of flow recorders located on bed-rock controls.[6,21] In investigations conducted in the Upper Rio Grande,[2] the Pecos River[4] and other river valleys,[23] engineers have used the inflow-outflow method to determine the consumptive use in irrigated valleys containing land areas up to 400,000 acres.

In the Upper Rio Grande Valley investigation the inflow-outflow method was considered to include the measurement of the amount of water flowing into and out of a given area, including precipitation and change in ground-water storage. Thus, valley consumptive use (U) is equal to the amount of water that flows into the valley during a 12-month year (I), plus the yearly precipitation on the valley floor (R), plus the water in ground storage at the beginning of the year (G_s), minus the amount of water in ground storage at the end of the year (G_e), minus the yearly outflow (O). All amounts are measured in acre-feet. This relation may be expressed by the equation

$$U = (I + R) + (G_s - G_e) - O \qquad (4)$$

The difference between the storage of capillary water at the beginning and end of the year is considered negligible. It is also assumed that stream measurements are made on bed-rock controls and there is little or no subsurface flow. Example of inflow-outflow measurement in several typical areas are given in Table 5.

Integration Method.—Briefly stated, the integration method determines consumptive use by the summation of the products of consumptive use for each crop, times its area, plus the consumptive use of natural vegetation times its area, plus water surface evaporation times water surface area, plus evaporation from bare land times its area. This method was used in the Upper Rio Grande Basin[2] and the Pecos River[4] investigation to determine valley consumptive use.

Before the integration method can be used successfully, it is necessary to know unit evapo-transpiration, or consumptive use of water, and the areas of various classes of agricultural crops, natural vegetation, bare land, and water surfaces. Unit values of the evapo-transpiration can be obtained by soil-moisture, tank, or some of the other methods previously described. By using aerial maps and field surveys, the areas of the various types or vegetative cover and the land and water surface areas can be determined, and the valley consumptive use computed.[2,4]

Effective Heat.—Many formulas have been developed for determining evaporation from meteorological observations, but formulas for estimating

[23] "Consumptive Use of Water for Agriculture," by Robert L. Lowry, Jr., and Arthur F. Johnson, *Transactions*, ASCE, Vol. 107, 1942, p. 1243.

consumptive use are not so numerous. A few methods for determining consumptive use, based on climatic factors, have been suggested and have been found to give reasonable results. For many years irrigation engineers have used temperature data in estimating valley consumptive use of water in areas of the West.[5] C. R. Hedke developed the effective heat method on the basis of studies of the Rio Grande. By this method consumptive use is estimated from a study of the heat units available to the crops of a particular valley. It assumes that there is a linear relation between the amount of water consumed and the quantity of available heat. Studies of the Bureau of Reclamation (USBR), United States Department of the Interior,[23] in 1941 developed a somewhat similar method that has been employed by the USBR in making its estimates of consumptive use. This method assumes a linear relation between consumptive use and accumulated daily maximum temperatures above 32° F during the growing season.

TABLE 5.—EXAMPLES OF VALLEY CONSUMPTIVE USE OF WATER DETERMINATIONS BY INFLOW-OUTFLOW METHOD

Location	Year	Area (acres)	Annual Consumptive Use		Authority
			Total (acre-feet)	Average (feet)	
San Luis Valley, Colo.	1925–1935	400,000	664,900	1.66	Blaney-Rohwer[a]
San Luis Valley, Colo.	1936	400,000	685,423	1.71	Blaney-Rohwer[a]
San Luis Valley, Colo.	1930–1932	17,300	26,215	1.52	Tipton-Hart[a]
Isleta-Belen, N. Mex.	1936	17,500	38,700	2.28	Blaney-Morin[a]
Mesilla Valley, N. Mex.	1919–1935	109,000	297,756	2.73	Blaney-Israelsen[a]
Mesilla Valley, N. Mex.	1936	110,418	303,683	2.75	Blaney-Israelsen[a]
Carlsbad, N. Mex.	1921–1939	51,700	129,752	2.51	Blaney-Morin-Criddle[b]
Carlsbad, N. Mex.	1940	51,700	119,898	2.33	Blaney-Morin-Criddle[b]
New Fork, Wyo.	1939–1940	25,000	....	1.59	Lowry-Johnson[c]
Michigan-Illinois-Colo.	1938–1940	43,000	....	1.50	Lowry-Johnson[c]
Uncompahgre, Colo.	1938–1940	137,700	....	2.28	Lowry-Johnson[c]

[a] "Water Utilization, Upper Rio Grande Basin," by Harry F. Blaney, Paul A. Ewing, O. W. Israelsen, Carl Rohwer, and F. C. Scobey, National Resources Committee, Washington, D. C., February, 1938, Part III. [b] "Consumptive Water Use and Requirements: Report of the Participating Agencies, Pecos River," by Harry F. Blaney, Paul A. Ewing, Karl V. Morin, and Wayne D. Criddle, Joint Investigation of the National Resources Planning Board, Washington, D. C., June, 1942. [c] "Consumptive Use of Water for Agriculture," by Robert L. Lowry, Jr., and Arthur F. Johnson, *Transactions*, ASCE, Vol. 107, 1942, p. 1243.

In 1940, in connection with the Pecos River Joint Investigation,[4] a method of estimating consumptive use by natural ground-water vegetation and by irrigated crops having access to an ample water supply was developed. Correlation of the relationship between evapo-transpiration, evaporation, temperature, percent of daytime hours, length of growing season, and humidity was used in the estimate.[24] In 1945 this method was modified to make possible estimates of consumptive use for areas in which humidity records are not available.[25] This method has been used by the Soil Conservation Service and other agencies in estimating rates of water consumption in many areas.

[24] "Evaporation and Consumptive Use of Water Empirical Formulas," by Harry F. Blaney and Karl V. Morin, *Transactions*, Part I, Am. Geophysical Union, August, 1942, p. 76.

[25] "A Method of Estimating Water Requirements in Irrigated Areas from Climatological Data," by Harry F. Blaney and Wayne D. Criddle, Div. of Irrigation and Water Conservation, Soil Conservation Service, U. S. Dept. of Agriculture, Logan, Utah, 1945.

Correlation of Water-Use, Climatological Data and Other Data

Actual measurements of consumptive use under each of the physical and climatical conditions of any large area are expensive and time consuming. Therefore, some rapid method of transferring the results of careful measurements, made in several areas, to other areas of similar conditions is needed. The Division of Irrigation and Water Conservation, Soil Conservation Service, has developed such a method to estimate rates of water consumption.[26,27] Briefly, the procedure is to correlate existing consumptive-use data with monthly temperature, percentage of daytime hours, precipitation, frost-free (growing) period, or irrigation season. The coefficients so developed for different crops are used to translocate or transpose consumptive-use data from one section to other areas in which climatological data alone are available.

TABLE 6.—Tentative Normal Consumptive-Use Coefficients for the More Important Irrigated Crops and Natural Vegetation of the West

Item	Length of growing season or period	Consumptive-use coefficient (K)
(*a*) Irrigated Land		
Alfalfa	frost-free	0.85
Beans	3 months	.65
Corn	4 months	.75
Cotton	7 months	.62
Citrus orchard	7 months	.55
Deciduous orchard	frost-free	.65
Pasture, grass, hay, annuals	frost-free	.75
Potatoes	3 months	.70
Rice	3 to 4 months	1.00
Small grains	3 months	.75
Sorghum	5 months	.70
Sugar beets	5½ months	.70
(*b*) Natural Vegetation[a]		
Very dense (large cottonwoods, willows)	frost-free	1.30
Dense (tamarisk, willows)	frost-free	1.20
Medium (small willows, tamarisk)	frost-free	1.00[b]
Light (saltgrass, sacaton)	frost-free	.80

[a] Ample moisture available from ground water or water table. [b] $K = 1.00$ for lake evaporation in arid areas and 0.90 for lake evaporation in coastal areas.

Although it is recognized that consumptive use of water is affected by numerous independent and related variables, records of temperatures and precipitation are by far the most universally available data throughout the western states. Research studies also indicate that, of all the climatic factors, these elements, together with daylight, undoubtedly have the greatest in-influence on plant growth. Disregarding the unmeasured factors, consumptive use varies with the temperature and the extent of daytime hours, and with the available moisture (precipitation, irrigation, and ground water). By multiply-

[26] "Irrigation Practice and Consumptive Use of Water in Salinas Valley, California," by Harry F. Blaney and Paul A. Ewing, Div. of Irrigation and Water Conservation, Soil Conservation Service, U. S. Dept. of Agriculture, Los Angeles, Calif., June, 1946.

[27] "Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data," by Harry F. Blaney and Wayne D. Criddle, Div. of Irrigation and Water Conservation, Soil Conservation Service, U. S. Dept. of Agriculture, SCS-TP-96, Washington, D. C., 1950.

ing the mean monthly temperature (t) by the monthly percentage of daytime hours of the year (p), a monthly consumptive-use factor (f) is obtained. Then it is assumed that the consumptive use varies directly as this factor when an ample water supply is available. Expressed mathematically

$$U = K F = \Sigma k f \qquad (5)$$

in which U is the consumptive use of crop (or evaporation) in inches for any period; F is the sum of the monthly consumptive-use factors for the period (sum of the products of mean monthly temperature and monthly percentage of daytime hours of the year); K is the empirical consumptive-use coefficient (irrigation season or growing period); and the other terms are as previously defined.

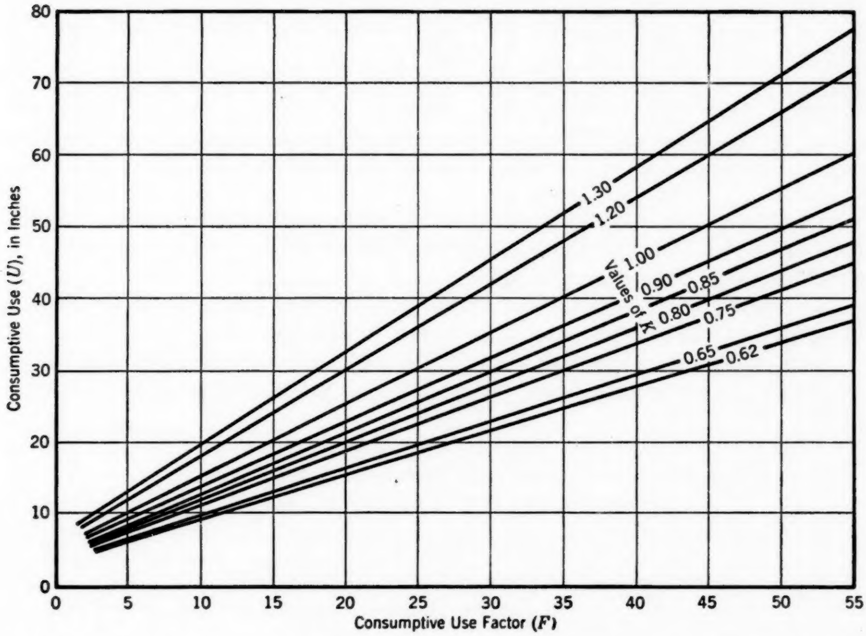

Fig. 3.—Relation of Consumptive Use to Temperature and Percentage of Daylight Hours

The consumptive-use factor (F) for any period may be computed for areas in which monthly temperature records are available. Then, by knowing the consumptive-use coefficient (k) for a particular crop in some locality, an estimate of the water use by the same crop in some other area may be made by application of Eq. 5.

The consumptive-use coefficients (K) for the more important irrigated crops (grown under normal conditions in the West) and natural vegetation are shown in Table 6. These coefficients were developed from actual measurements of consumptive use in tank and soil-moisture field studies; and inflow-

outflow measurements made throughout the West over a period of years by the Division of Irrigation and Water Conservation and other agencies. These coefficients are based on the assumption that the plants or trees receive a full water supply throughout the growing season or frost-free period. Fig. 3

TABLE 7.—MONTHLY PERCENTAGE OF DAYTIME HOURS OF THE YEAR FOR LATITUDES 24° TO 50° NORTH OF THE EQUATOR

Month	Latitudes in Degrees North of Equator													
	24	26	28	30	32	34	36	38	40	42	44	46	48	50
January	7.58	7.49	7.40	7.30	7.20	7.10	6.99	6.87	6.76	6.62	6.49	6.33	6.17	5.98
February	7.17	7.12	7.07	7.03	6.97	6.91	6.86	6.79	6.73	6.65	6.58	6.50	6.42	6.32
March	8.40	8.40	8.39	8.38	8.37	8.36	8.35	8.34	8.33	8.31	8.30	8.29	8.27	8.25
April	8.60	8.64	8.68	8.72	8.75	8.80	8.85	8.90	8.95	9.00	9.05	9.12	9.18	9.25
May	9.30	9.38	9.46	9.53	9.63	9.72	9.81	9.92	10.02	10.14	10.26	10.39	10.53	10.69
June	9.20	9.30	9.38	9.49	9.60	9.70	9.83	9.95	10.08	10.21	10.38	10.54	10.71	10.93
July	9.41	9.49	9.58	9.67	9.77	9.88	9.99	10.10	10.22	10.35	10.49	10.64	10.80	10.99
August	9.05	9.10	9.16	9.22	9.28	9.33	9.40	9.47	9.54	9.62	9.70	9.79	9.89	10.00
September	8.31	8.31	8.32	8.34	8.34	8.36	8.36	8.38	8.38	8.40	8.41	8.42	8.44	8.44
October	8.09	8.06	8.02	7.99	7.93	7.90	7.85	7.80	7.75	7.70	7.63	7.58	7.51	7.43
November	7.43	7.36	7.27	7.19	7.11	7.02	6.92	6.82	6.72	6.62	6.49	6.36	6.22	6.07
December	7.46	7.35	7.27	7.14	7.05	6.92	6.79	6.66	6.52	6.38	6.22	6.04	5.86	5.65
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

shows the relation of consumptive use (U); consumptive-use factor (F); and coefficient (K). Monthly percentage of annual daytime hours computed from sunshine tables[28] are shown in Table 7.

Examples of consumptive-use rates in the Upper Colorado River Basin,[3] computed by the above method, are shown in Table 8.

The consumptive-use coefficients shown in Table 6 are suitable for average conditions in the semiarid areas of the West. Studies to develop correction

TABLE 8.—ESTIMATES OF NORMAL UNIT CONSUMPTIVE-USE RATES DURING THE IRRIGATION PERIOD FOR IRRIGATED CROPS FOR SEVERAL LOCALITIES IN THE UPPER COLORADO RIVER BASIN

Location	Normal Rate of Consumptive Use, in Inches[a]			
	Alfalfa	Pasture	Grains	Corn
Chinle, Arizona	28.3	24.2	15.4	20.1
Eagle, Colorado	18.5	16.2	11.6	11.6
Cortez, Colorado	24.5	21.5	14.6	18.9
Durango, Colorado	22.9	20.1	14.0	17.1
Farmington, New Mexico	32.1	28.4	15.3	20.4
Green River, Utah	32.5	28.6	16.2	21.7
Price, Utah	26.7	23.5	15.4	19.9
Eden, Wyoming	17.2	15.1	13.4	....
Pinedale, Wyoming	14.8	13.0	....	....

[a] Values used in the formula $U = KF$ are: Alfalfa, 0.85; pasture, 0.75; grain, 0.75; and corn, 0.75.

factors for humid conditions in the eastern states have been undertaken. It is anticipated that evaporation, humidity, or solar radiation records can be

[28] "Sunshine Tables," *Bulletin No. 805*, Weather Bureau, U. S. Dept. of Agriculture, Washington, D. C., 1905.

used for this purpose until measured consumptive-use data are available. Basic solar radiation data are now available at many stations throughout the United States.

Analysis of Irrigation and Precipitation Records

In the consumptive-use studies conducted on the Pecos River in 1940, a method of determining unit consumptive use for various agricultural crops from irrigation and precipitation was developed.[4] This method has been successfully employed in several areas in California.[26] It consists of estimating evaporation and transpiration losses during the irrigation season and winter period based on data of the number of irrigations and depth of water applied, farm duty of water, and efficiency of irrigation water application for various crops and soils; and precipitation and evaporation from free water surface. Precipitation may be a major factor in winter consumptive use.

A field survey of conditions through the Pecos Valley area was made. Water superintendents of irrigation district and water companies, engineers, county farm advisors, and farmers were interviewed to ascertain the quantity of irrigation water supplied to various crops, both for the growing season and the winter period. Precipitation, irrigation, and other records were collected and estimates made of the efficiency of irrigation for various crops in the different areas. The latter data were supplemented by water-application efficiency studies, made on typical farms by measuring the quantity of water applied and taking soil samples before and after irrigation. By this means it was possible to determine the proportion of soil moisture available for crop transpiration use within the root zone. These data were analyzed and the unit rate of water consumption for each crop computed. The total consumptive use in acre-feet may be computed by multiplying unit values of consumptive use for each crop by its area.

Acknowledgment

This paper serves as an introduction to several others on this same general subject[29,30,31,32] and should provide the background necessary for complete understanding of the specialized phases of the field.

[29] "Consumptive Use in the Rio Grande Basin," by Robert L. Lowry, *Proceedings-Separate No. 97*, ASCE, November, 1951.

[30] "Consumptive Use of Water by Forest and Range Vegetation," by L. R. Rich, *Proceedings-Separate No. 90*, ASCE, October, 1951.

[31] "Consumptive Use of Water on Irrigated Land," by Wayne D. Criddle, *Proceedings-Separate No. 98*, ASCE, November, 1951.

[32] "Consumptive Use in Municipal and Industrial Areas," by George B. Gleason, *Proceedings-Separate No. 99*, ASCE, November, 1951.

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